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APPLICATION FOR UNITED STATES LETTERS PATENT

FOR

METHOD AND APPARATUS FOR MULTI-FREQUENCY NMR DIFFUSION MEASUREMENTS IN THE PRESENCE OF INTERNAL MAGNETIC FIELD GRADIENTS

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FIELD OF THE INVENTION

[0001] This invention relates to apparatus and techniques for making nuclear magnetic resonance (NMR) measurements in boreholes and to methods for determining magnetic characteristics of formations traversed by a borehole. Specifically, the invention relates to design an accurate NMR measurement technique, which is aimed at defining the diffusion properties of the fluid in the pore matrix in the presence of the internal magnetic field gradients.

BACKGROUND OF THE INVENTION

[0002] A variety of techniques have been used in determining the presence and in estimating quantities of hydrocarbons (oil and gas) in earth formations. These methods are designed to determine parameters of interest, including among other things, porosity, fluid content, and permeability of the rock formation surrounding the wellbore drilled for recovering hydrocarbons. Typically, the tools designed to provide the desired information are used to log the wellbore. Much of the logging is done after the wellbores have been drilled. More recently, wellbores have been logged while drilling of the wellbores, which is referred to as measurement-while-drilling ("MWD") or logging-while-drilling ("LWD"). Measurements have also been made when tripping a drillstring out of a wellbore: this is called measurement-while-tripping ("MWT").

[0003] One evolving technique uses nuclear magnetic resonance (NMR) logging tools and methods for determining, among other things porosity, hydrocarbon saturation and

permeability of the rock formations. NMR logging tools excite the nuclei of the fluids in the geological formations in the vicinity of the wellbore so that certain parameters such as spin density, longitudinal relaxation time (generally referred to in the art as "T_1"), and transverse relaxation time (generally referred to as "T_2") of the geological formations can be estimated. From such measurements, formation parameters such as porosity, permeability and hydrocarbon saturation are determined, which provides valuable information about the make-up of the geological formations and the amount of extractable hydrocarbons.

[0004] A typical NMR tool generates a static magnetic field $\mathbf{B_0}$ in the vicinity of the wellbore and an oscillating field $\mathbf{B_1}$ in a direction perpendicular to $\mathbf{B_0}$. This oscillating field is usually applied in the form of short-duration pulses. The purpose of the $\mathbf{B_0}$ field is to polarize the magnetic moments of nuclei parallel to the static field and the purpose of the $\mathbf{B_1}$ field is to rotate the magnetic moments by an angle controlled by the width t_p and the amplitude B_1 of the oscillating pulse. For NMR logging, the most common sequence is the Carr-Purcell-Meiboom-Gill ("CPMG") sequence that can be expressed as

$$TW - 90 - (\tau - 180 - \tau - \text{echo})_n \qquad (1)$$

where TW is a wait time, 90 is a 90°tipping pulse, 180 and is a 180° refocusing pulse and 2τ = TE is the interecho spacing.

[0005] After being tipped by 90°, the magnetic moment precesses around the static field at a particular frequency known as the Larmor frequency ω , given by $\omega = \gamma B_0$, where B_0

is the field strength of the static magnetic field and γ is the gyromagnetic ratio. At the same time, the magnetic moments return to the equilibrium direction (i.e., aligned with the static field) according to a decay time known as the "spin-lattice relaxation time" or T_1 . . Inhomogeneities of the B_0 field result in dephasing of the magnetic moments and to remedy this, a 180° pulse is included in the sequence to refocus the magnetic moments. This refocusing gives a sequence of *n* echo signals. These echo sequences are then processed to provide information about the relaxation times.

[0006] Also associated with the spin of molecular nuclei is a second relaxation time, T_2, called the transverse or spin--spin relaxation time. At the end of a 90° tipping pulse, all the spins are pointed in a common direction perpendicular, or transverse, to the static field, and they all precess at the Larmor frequency. However, because of small fluctuations in the static field induced by other spins or paramagnetic impurities, the spins precess at slightly different frequencies and the transverse magnetization dephases with a relaxation time T_2.

[0007] Interpretation of NMR core or log data is often started by inverting the time-domain CPMG echo decay into a T_2 parameter domain distribution. In general, the T_2 of fluids in porous rocks depends on the pore-size distribution and the type and number of fluids saturating the pore system. Because of the heterogeneous nature of porous media, T_2 decays exhibit a multiexponential behavior. The basic equation describing the transverse relaxation of magnetization in fluid saturated porous media is

$$M(t) = \int_{T_{2\min}}^{T_{2\max}} P(T_2) e^{-t/T_2} dT_2 \qquad (2)$$

where M is magnetization and effects of diffusion in the presence of a magnetic field gradient have not been taken into consideration. **Eq.(2)** is based on the assumption that diffusion effects may be ignored. In a gradient magnetic field, diffusion causes atoms to move from their original positions to new ones which also causes these atoms to acquire different phase shifts compared to atoms that did not move. This contributes to a faster rate of relaxation.

[0008] The effect of field gradients is given by an equation of the form

$$\frac{1}{T_2} = \frac{1}{T_{2bulk}} + \frac{1}{T_{2surface}} + \frac{1}{T_{2diffusion}} \qquad (3)$$

where the first two terms on the right hand side are related to bulk relaxation and surface relaxation while the third term is related to the field gradient G by an equation of the form

$$T_{2diffusion} = \frac{C}{TE^2 \cdot G^2 \cdot D} \qquad (4)$$

where TE is the interecho spacing, C is a constant and D is the diffusivity of the fluid.

[0009] US Patent 6512371 to *Prammer,* et. al., discloses a well logging system and method for detecting the presence and estimating the quantity of gaseous and liquid hydrocarbons in the near-wellbore zone. The system uses a gradient-based, multiple-frequency NMR logging tool to extract signal components characteristic for each type of

hydrocarbon. Measurements at different frequencies are interleaved to obtain, in a single logging pass, multiple data streams corresponding to different recovery times and/or diffusivity for the same spot in the formation.

[0010] One of the main difficulties in defining self-diffusion parameters of the fluid in the pore matrix is related to the fact that different fluids having the same relaxation times and different diffusion coefficients cannot be effectively separated. Due to the practical limitation of the signal-to-noise ratio, none of the existing inversion techniques allow an effective and stable reconstruction of both the relaxation and diffusion spectra.

[0011] Another difficulty in relaxation and diffusion spectra reconstruction is caused by internal magnetic gradients. Typically, the values of the internal gradients are unknown. Thus, the diffusion parameters cannot be correctly defined if the internal gradients are not considered in both the measurement and interpretation scheme.

[0012] To separate the relaxation and diffusion process, US Patent 6,597,171 to *Hurlimann,* et al. introduced the so-called diffusion editing sequence allowing an effective separation of the relaxation and diffusion process. The diffusion editing sequence is a short pulse sequence allowing different sensitivities of the measured NMR signal to the self-diffusion coefficients. Several different types of diffusion editing sequences are described in *Hurlimann,* '171, including an inversion recovery sequence and a driven equilibrium sequence. After the diffusion editing sequence a regular CPMG sequence with a short TE is applied to acquire NMR data. As demonstrated by

Hurlimann '171 the diffusion editing technique allows for a 2D map with a relaxation time T_2 , in one direction and diffusion coefficient in a second direction. However, this technique fails to define the diffusion coefficient if internal magnetic field gradients are present in the formation.

[0013] The internal gradient issue, in relation to the diffusion measurements, was discussed in US Patent 5,698,979 to *Taicher, et al.*, having the same assignee as the present application and the contents of which are incorporated herein by reference. *Taicher* suggested the use of dual frequency measurements when two different values of a static magnetic field within the porous medium are used to find decay rates for each frequency. It showed that under the assumption that internal gradients, G_i , are proportional to a static magnetic field and the difference in the magnetic susceptibility between the fluid and the solid matrix, the diffusion coefficients could be uniquely defined. The *Taicher* approach does not address differentiating fluids with the same relaxation times and different diffusion coefficients (in other words, generating a 2D map with a relaxation time, T_2, in one direction and a diffusion coefficient in a second direction).

[0014] There is a need for a system and method of determining diffusion coefficients and relaxation times of fluids in an earth formation that takes into account internal field inhomogeneities. Such a system and method should preferably be efficient in terms of power consumption and acquisition time. The present invention satisfies this need and provides several advantages that would be recognized by those versed in the art.

SUMMARY OF THE INVENTION

[0015] The present invention is a method and apparatus for determining a parameter of interest of an earth formation using a Nuclear Magnetic Resonance (NMR) tool conveyed in a borehole in the earth formation. A magnet on the NMR tool applies a static magnetic field to the earth formation and aligns nuclear spins. The effective magnetic field gradient is different from the applied static magnetic field due to the presence of an internal field gradient. A series of radio frequency (RF) diffusion editing magnetic pulse sequence are applied. In a diffusion editing sequence, a latter portion of the pulse sequence refocuses a final echo produced by the earlier portion of the pulse sequence. The diffusion editing sequence is applied at one or more different frequencies. From the ensemble of received signals, the T_2 spectral distribution and the diffusion coefficients are determined. These determinations make it possible to determine paramters of interest of the earth formation such as total porosity, clay bound water, bound volume irreducible, gas saturation and oil saturation may be determined..

[0016] The earlier portion of a diffusion editing pulse sequence could be a CPMG sequence, a modified CPMG sequence (i.e., tipping angle of refocusing pulse less than 180^0), an inversion recovery sequence or a driven equilibrium sequence. For the case where the earlier portion includes a CPMG or a modified CPMG sequence, the refocusing-pulse spacing is larger than refocusing pulse spacing for the latter portion of a diffusion editing sequence. The latter portion of a diffusion editing sequence could be a

CPMG sequence or a modified CPMG sequence having a refocusing pulse with a tipping angle of less than 180^0. The interval between refocusing pulses should be as small as possible.

[0017] The number of diffusion editing pulse sequences is selected to be at least equal to the number of desired components of the resolved T_2 spectrum. The number of frequencies at which measurements are made is equal to or greater than the number of diffusion components. In the latter case, an overdetermined system of equations is solved.

[0018] The NMR tool may be conveyed into the borehole on a wireline, coiled tubing, or a drillstring.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] The present invention is best understood with reference to the following figures in which like numerals refer to like elements, and in which:

Fig. 1 depicts diagrammatically an NMR logging tool in a borehole;

Fig. 2 shows an exemplary configuration of magnets, antenna and shield suitable for use with the present invention;

Figs. 3a and 3b show simulated echo trains using a pulse sequence of the present invention for two different B pulse rotation angles; and

Figs. 4a and 4b schematically illustrate operations in the method of the present invention.

DETAILED DESCRIPTION OF THE EMBODIMENT

[0020] Fig. 1 depicts a borehole **10** drilled in a typical fashion into a subsurface geological formation **12** to be investigated for potential hydrocarbon producing reservoirs. An NMR logging tool **14** has been lowered into the hole **10** by means of a cable **16** and appropriate surface equipment (represented diagrammatically by a reel **18)** and is being raised through the formation **12** comprising a plurality of layers **12a** through **12g** of differing composition, to log one or more of the formation's characteristics. The NMR logging tool may be provided with bowsprings **22** to maintain the tool in an eccentric position within the borehole with one side of the tool in proximity to the borehole wall. The permanent magnets **23** provide the static magnetic field . Signals generated by the tool **14** are passed to the surface through the cable **16** and from the cable **16** through another line **19** to appropriate surface equipment **20** for processing, recording, display and/or for transmission to another site for processing, recording and/or display. Alternatively, the processor may be located at a suitable position (not shown) downhole, e.g., in the logging tool **14**.

[0021] Fig. 2 (prior art) schematically illustrates an exemplary embodiment of an apparatus suitable for use with the method of the present invention. This is discussed in detail in U.S. Patent 6,348,792 of *Beard et. al.*, having the same assignee as the present invention; the contents of which are fully incorporated herein by reference. The tool cross-sectional view in **Fig. 2** illustrates a main magnet **217**, a second magnet **218** and a transceiver antenna comprising wires **219** and core material **210**. The arrows **221** and **223** depict the polarization (e.g., from the South pole to the North pole) of the main magnet

217 and the secondary magnet 218. A noteworthy feature of the arrangement shown in Fig. 2 is that the polarization of the magnets providing the static field is towards the side of the tool, rather than towards the front of the tool (the right side of Fig. 2).

[0022] The second magnet 218 is positioned to augment the shape of the static magnetic field by adding a second magnetic dipole in close proximity to the RF dipole defined by the wires 219 and the soft magnetic core 210. This positioning moves the center of the effective static dipole closer to the RF dipole, thereby increasing the azimuthal extent of the region of examination. The second magnet 218 also reduces the shunting effect of the high permeability magnetic core 210 on the main magnet 217. In the absence of the second magnet, the DC field would be effectively shorted by the core 210. Thus, the second magnet, besides acting as a shaping magnet for shaping the static field to the front of the tool (the side of the main magnet) also acts as a bucking magnet with respect to the static field in the core 210. Those versed in the art will recognize that the bucking function and a limited shaping could be accomplished simply by having a gap in the core; however, since some kind of field shaping is required on the front side of the tool, in a preferred embodiment of the invention, the second magnet serves both for field shaping and for bucking. If the static field in the core 210 is close to zero, then the magnetostrictive ringing from the core is substantially eliminated.

[0023] Within the region of investigation, the static field gradient is substantially uniform and the static field strength lies within predetermined limits to give a substantially uniform Larmor frequency. Those versed in the art will recognize that the combination of

field shaping and bucking could be accomplished by other magnet configurations than those shown in **Fig. 2.**

[0024] Still referring to **Fig. 3,** the transceiver wires **219** and core pieces **210** may be separated as far as possible towards the sides of the tool. This separation increases the transceiver antenna efficiency by increasing the effective RF dipole of the antenna and augments the shape of the RF magnetic field isolines so that they better conform to the static magnetic field isolines. The secondary magnet may be made of nonconducting material to minimize eddy currents induced by the RF field, thereby increasing the RF antenna efficiency. The antenna core may be made of a powdered soft magnetic material, other than ferrite, as disclosed in U.S. Patent 6,452,388 of *Reiderman et. al.* having the same assignee as the present invention and the contents of which are fully incorporated herein by reference. The antenna core has a high saturation flux density and comprises particles of powdered material small enough to be transparent to the RF magnetic field.

[0025] For the purposes of the method of the present invention, the formation is characterized by a model having a multi-exponential spectrum of the form:

$$T_2^{(1)}, T_2^{(2)}, T_2^{(3)}, \cdots T_2^{(i)}, \cdots T_2^{(M)} \qquad (5)$$

Associated with each $T_2^{(i)}$, there are several diffusion coefficient values. These are denoted by

$$D_i^{(1)}, D_i^{(2)}, \cdots D_i^{(N)} \qquad (6)$$

The corresponding amplitudes are denoted by:

$$A_{i0}^{(1)}, A_{i0}^{(2)}, \cdots A_{i0}^{(N)} \qquad (7)$$

Without loss of generality, it can be assumed that the same number of terms N for each i-term of the T_2 distribution is used to represent the diffusion distribution function. The present invention establishes a set of measurements, and an adequate processing technique, for determining both transversal time and diffusion distribution function in the presence of internal field gradients G_I and an external magnetic field gradient G.

[0026] The internal gradients, G_I, are proportional to the magnitude of the applied magnetic field, H_0, and the difference in the magnetic susceptibility, $\Delta\chi$, between the fluid and the solid matrix

$$G_I = H_0 \Delta\chi / 4R_\rho = \alpha H_0 \qquad (8)$$

where R_ρ - is the effective radius of the pore matrix and $\alpha = \Delta\chi/4R_\rho$. The effective gradient, G_e, can be is estimated as:

$$G_e = \sqrt{G^2 + G_I^2} \qquad (9)$$

Each exponential term decays according to the following expression:

$$A_i^j(t) = A_{io}^{(j)} \cdot \exp\left(-t / T_2^{i^*}\right) \qquad (10)$$

where A_{i0} corresponds to the total number of protons having a transversal relaxation time, T_i, and $T_2^{i^*}$ represents an effective relaxation decay comprised of two different components – decay due to transversal relaxation T_2 and decay due to diffusion process:

$$\frac{1}{T_2^{i*}} = \frac{1}{T_2^i} + \frac{1}{12}\gamma^2 \cdot G_e^2 \cdot D \cdot TE^2 \qquad (11)$$

where γ - the gyromagnetic ratio, G_e – an effective magnetic field gradient, TE is the echo spacing,

[0027]Eqns. (10) and **(11)**, shows that the signal decay due to diffusion, D, increases with time. In a manner similar to that discussed by *Hurlimann*'171 , one can apply a diffusion editing sequence to separate the diffusion and relaxation process. Applying the standard CPMG sequence with a small echo spacing TE, the diffusion will not have an impact on the train and the T_2 spectrum can be reconstructed. Applying a second sequence with an increased value TE_{long} for the first two echo-spacings, and then following it by a series of 180° B-pulses with a small TE (a diffusion editing sequence), the decay rate of the two trains after time $t_d = 2TE_{long}$ will be the same. The initial amplitude of the second echo train is smaller compared to the amplitude of the first echo train measured from the standard CPMG.

[0028] If the diffusion is described as the diffusion distribution function, the signal drop for each T_2^i term is defined by the series of exponential terms. The series has as many exponents N as the number of diffusion coefficients in the representation of the diffusion distribution function. In the case of the diffusion editing sequence, the signal decay of the train amplitude for large times, t_d, is defined by the expression:

$$A(t) = \sum_{i=1}^{M} [A_{i0}^{(1)} \exp(-\frac{1}{6}\gamma^2 G_e^2 D_i^{(1)} TE_{long}^3) + A_{i0}^{(2)} \exp(-\frac{1}{6}\gamma^2 G_e^2 D_i^{(2)} TE_{long}^3) + \ldots A_{i0}^{(N)} \exp(-\frac{1}{6}\gamma^2 G_e^2 D_i^{(N)} TE_{long}^3)] \exp(-\frac{t}{T_2^i}) \quad (12)$$

[0029] When there is no internal magnetic field gradient and G_e represents an external gradient only, the technique described in *Hurlimann*'171 will provide a sufficient set of data for diffusion distribution reconstruction. To reconstruct the N terms of the diffusion distribution function, at least N different measurements with different diffusion editing times, TE_{long} are required. However, in practice, the condition of zero internal magnetic field gradient is not usually satisfied. Internal magnetic gradients are present in the formation and do affect the measurements. For this reason the approach described in *Hurlimann*'171 will not be sufficient to determing the diffusion distribution coefficients, $D_i^{(j)}$. What can be determined is the product of the coefficient and the effective magnetic gradient. The effective magnetic field gradient is unknown, hence the diffusion coefficients cannot be determined.

[0030] The present invention reconstructs the diffusion distribution in the presence of the internal magnetic gradients by using additional measurements carried out in different gradient fields. For any given value TE_{long} of the diffusion editing sequence, the expression in the square brackets of **eqn. (12)** can be considered as an amplitude corresponding to the relaxation term $T_2^{(i)}$ of the multi-exponential spectrum. This may be defined as an equivalent amplitude spectrum. This equivalent spectrum can be

reconstructed from the data corresponding to each diffusion editing sequence by prior art methods. An example of such a reconstruction using singular value decomposition is given in US Patent 5,517,115 to *Prammer* . Other methods also exist for performing a spectral decomposition, any of which could be used.

[0031] In the present invention, a series of K diffusion editing sequences is applied where $K \geq N$. The K distributions of T_2 can be reconstructed by inversion. For each i-term of T_2, we have a series of reconstructed amplitudes, S_i^j. The following system of equations describes the relation between the amplitudes, S_i^j, and diffusion distribution, $D_i^{(j)}$:

$$\begin{cases} A_{i0}^{(1)} \cdot \exp(-1/6\gamma^2 G_e^2 D_i^{(1)} TE_{long(1)}^3) + \quad ....A_{i0}^{(N)} \cdot \exp(-1/6\gamma^2 G_e^2 D_i^{(N)} TE_{long(1)}^3) = S_i^{(1)} \\ A_{i0}^{(1)} \cdot \exp(-1/6\gamma^2 G_e^2 D_i^{(1)} TE_{long(2)}^3) + \quad ....A_{i0}^{(N)} \cdot \exp(-1/6\gamma^2 G_e^2 D_i^{(N)} TE_{long(2)}^3) = S_i^{(2)} \\ ---------- \\ A_{i0}^{(1)} \cdot \exp(-1/6\gamma^2 G_e^2 D_i^{(1)} TE_{long(K)}^3) + \quad ....A_{i0}^{(N)} \cdot \exp(-1/6\gamma^2 G_e^2 D_i^{(N)} TEt_{long(K)}^3) = S_i^{(K)} \end{cases}$$

(13)

Eqn. (13) can be written in terms of a generalized parameter Z in the form:

$$\begin{cases} A_{i0}^{(1)} \cdot \exp(-z_1 / Z_i^{(1)}) + \quad ....A_{i0}^{(N)} \cdot \exp(-z_1 / Z_i^{(N)}) = S_i^{(1)} \\ A_{i0}^{(1)} \cdot \exp(-z_2 / Z_i^{(1)}) + \quad ....A_{i0}^{(N)} \cdot \exp(-z_2 / Z_i^{(N)}) = S_i^{(2)} \\ ---------- \\ A_{i0}^{(1)} \cdot \exp(-z_K / Z_i^{(1)}) + \quad ....A_{i0}^{(N)} \cdot \exp(-z_K / Z_i^{(N)}) = S_i^{(K)} \end{cases} \qquad (14)$$

where $z_j = TE_{long(j)}^3$ and

$$Z_i^{(j)} = \frac{6}{\gamma^2 G_e^2 D_i^j} \qquad (15)$$

[0032] Eqn. (14) contains a set of exponential functions designed to cover all of the possible $Z_{(i)}$ values for which the individual amplitudes, $A_{i0}^{(j)}$, must be determined. In practice, the right hand side of the **eqn. (14)** is not defined exactly but with some error that depends on the level of the noise in the measurements and the accuracy in the reconstruction of the T_2 distribution. For this reason **eqn. (14)** should be treated in the sense of a least square problem with the number of the diffusion editing sequences, K, larger than the number of amplitudes, $A_{i0}^{(N}$.

[0033] After solving **eqn. (14)** and using **eqn. (15)** (i.e., by inversion) , the generalized parameter $Z_{(i)}^{(j)}$ and the product $P_i^{(j)}=G^2_e D_i^{(j)}$ for each diffusion term can be estimated. To define the diffusion coefficient, $D_i^{(j)}$, at least one more measurement conducted at a different gradient is needed. This additional measurement is done in a magnetic field, H_2, having the gradient, G_2, different from the first magnetic field, H_1, having the gradient, G_1. This condition gives the following system of equations:

$$\begin{cases} P_{1,i}^{(j)} = G_{e1}^2 D_i^{(j)} = (G_1^2 + \alpha H_1^2) \cdot D_i^{(j)} \\ P_{2,i}^{(j)} = G_{e2}^2 D_i^{(j)} = (G_2^2 + \alpha H_2^2) \cdot D_i^{(j)} \end{cases} \qquad (16)$$

From **eqn. (16)** the parameter, α, and coefficient, $D_i^{(j)}$, for each term of the diffusion distribution can be determined:

$$\alpha = \frac{G_2^2 P_{1,i}^{(j)} - G_1^2 P_{2,i}^{(j)}}{P_{2,i}^{(j)} H_1^2 - P_{1,i}^{(j)} H_2^2} \qquad (17)$$

and

$$D_i^{(j)} = \frac{P_{1,i}^{(j)}}{G_1^2 + \alpha H_1^2} \qquad (18)$$

[0034] To increase the accuracy in the diffusion distribution reconstruction, one embodiment of the invention uses multi-gradient measurements at several different, L, gradients. Then instead of **eqn. (16)**, the following system of equations applies:

$$\begin{cases} P_{1,i}^{(j)} = G_{e1}^2 D_i^{(j)} = (G_1^2 + \alpha H_1^2) \cdot D_i^{(j)} \\ P_{2,i}^{(j)} = G_{e2}^2 D_i^{(j)} = (G_2^2 + \alpha H_2^2) \cdot D_i^{(j)} \\ \vdots \qquad\qquad \vdots \qquad\qquad \vdots \\ P_{L,i}^{(j)} = G_{eL}^2 D_i^{(j)} = (G_L^2 + \alpha H_L^2) \cdot D_i^{(j)} \end{cases} \qquad (19)$$

Eqn. (19) should be treated as a least squares problem with the number of equations, L, not less than 2. By solving **eqn. (19)** the diffusion coefficients D_i^j comprising the diffusion distribution functions, will be defined for each $T_2^{(i)}$ term of the T_2 distribution. When $L > 2$, the system of equations is overdetermined. It should be noted that different gradients can be obtained easily using the gradient tool described above with reference to **Fig. 2**. When a tool such as that in **Fig. 2** is used, the two different gradients would correspond to two different frequencies and two different regions of examination. However, it is possible to get two different gradients at the same frequency using a suitable magnet configuration and a gradient coil on the NMR tool. In the latter case, the measurements could be made in either the same or in different regions of examination.

[0035] Reconstruction of both T_2 and the diffusion distribution requires a vast number of measurements. In one embodiment of the invention, power requirements are optimized using the methodology described in U.S. Patent 6,163,153 of *Reiderman et. al.* As described in the *Reiderman* '153 patent, NMR measurements in a gradient field with a reduced flip angle permit a better signal-to-noise ratio while consuming less DC power. The suggested pulse sequence in *Reiderman* '153 represents a CPMG sequence with the B-pulse rotation angle in the range of 90°-135°. In the case of multi-gradient and multi-TE_{long} measurements, the application of a reduced flip angle, if possible, could save a great deal of DC power while boosting the signal-to-noise ratio. Based on this, in one embodiment of the invention, the following pulse sequence is used:

$$W - 90_{\pm x} - TE_{long}/2 - \beta_{Y1} - TE_{long}/2 - echo_1 - TE_{long}/2 - \beta_{Y1} - TE_{long}/2 - echo_2 - (TE/2 - \beta_{Y2} - TE/2 - echo)_j \quad (20)$$

where j is the echo number in the train, W is the wait time, TE_{long} is the diffusion editing spacing, TE is the Carr-Purcell spacing, 90_x and β_{Y1} (or β_{Y2}) are the RF pulses providing rotation angles of 90 and β_1 (or β_2) degrees of the magnetization vector about the X and Y axis, respectively. The rotation angle, β_1, is set to be less than 180 ° or equal to 180°. The rotation angle, β_2, is set by adjusting the RF pulse duration and amplitude to compromise between peak power and excitation volume thickness. As discussed in *Reiderman* '153, the rotation angle β_2 is typically in the range of 90°-135°. The latter part of the pulse sequence (the term within parantheses) refocuses the last echo produced by the early part of the pulse sequence. The early (and the latter) part of the sequence

given by **eqn. (20)** are modified CPMG sequence with a refocusing angle less than 180°. This pulse sequence is schematically illustrated in **Fig. 3a**. The 90° pulse is denoted by **100**. The refocusing pulses are denoted by **101a, 101b, 101c, 101d....** while the echos are denoted by **103a, 103b, 103c, 103d**...

[0036] Fig.4b shows that by applying the new diffusion editing sequence **(20)** with a flip angle, β_Y =135° a stable echo train with a larger signal amplitude is received while consuming less DC power. (The amplitude of the train is increased due to the increase in the sensitive volume). For the example shown in **Fig. 3b,** TE_{long} = 8 ms, TE = 1ms, and $T_1 = T_2 = \infty$. The deviation of the echo train from an echo train with a 180° flip angle can be easily corrected by using a set of pre-calculated correction coefficients. To calculate the correction coefficients, **Fig. 4a** shows a simulated echo train signal for the diffusion editing sequence **eqn. (20)** with a rotation angle β_Y =180°. The ration of the corresponding amplitudes from **Fig. 4a** and **Fig. 4b** gives the correction coefficients for the reduced flip angle.

[0037] *Reiderman* '153 shows the derivation of the correction coefficients for $T_1 = T_2$. In co-pending U.S. patent application Ser. No. 09/976,493 of *Reiderman* et al., now U.S. Patent *******, it is shown that such correction factors can be derived for values of $T_1 \neq T_2$.

[0038] In an alternate embodiment of the invention, instead of the modified CPMG pulse sequence given by **eqn. (20)**, an inversion recovery sequence is used for the first part of the pulse sequence. This may be represented by:

$$180 - \tau_1 - 90_{\pm x} - \left[TE/2 - \beta_Y - TE/2 - echo\right]_j \qquad (21).$$

where 180 is a 180° inversion pulse, τ_1 is a wait time, TE is an interecho time and β_Y is a refocusing pulse with a tipping angle of Y. This pulse sequence is depicted in **Fig. 3b**. The initial 180° inversion pulse is shown by **110** and the rest of the sequence follows. In yet another embodiment of the invention, the first part of the pulse sequence is a driven equilibrium sequence as follows:

$$W - 90_{\pm x} - [\delta_j - 90_{\pm x} - (\Delta - \delta_j) - echo_{k,j}] - \left(TE/2 - \beta_Y - TE/2 - echo\right)_l \qquad (21a)$$

This is depicted in **Fig. 3c.** The initially 90° tipping pulse is denoted by **120** and the rest of the sequence follows.

[0039] Turning now to **Figs. 4a** and **4b**, an exemplary flow chart illustrating the method of the present invention is shown. The nuclear spins in a region of investigation of the earth formation are polarized **401**. Spin echo signals are then produced using a pulsed RF signal **403**. In one embodiment of the invention, the spin echo signals are produced using the modified CPMG pulse sequence denoted by **eqn. (20)**, i.e., with a B pulse flip angle of less than 180°. If a reduced flip angle B pulse is used, then amplitude corrections are applied **405** as discussed above and shown in *Reiderman* '153 and in the *Redierman*'493 application. In another embodiment of the invention, the B pulse flip angle is taken as 180°. In this case, **405** can be skipped. In either case, the value of TE is chosen to be as

short as possible to minimize the effect of diffusion on the relaxation process. Values of TE within the range of 0.5 ms – 2.0 ms are preferred. In yet another embodiment of the invention, the pulse sequence of **eqn. (21)** or **(21a)** is used, i.e., wherein a modified CPMG sequence follows an inversion recovery sequence or a driven equilibrium echo sequence.

[0040] The process described above is repeated for a plurality of different values of TE_{long} **407**, defining a plurality of diffusion editing sequences and corresponding signals. At **409**, data are acquired with whereTE_{long} = TE. This gives a reference signal for the diffusion editing process. At **411** and **413** the signals are inverted to get a T_2 distribution and the, the *Z* parameters, and the product $P_i^{(j)}=G^2_e D_i^{(j)}$. This is done solving **eqns. (14)-(15).** As noted above, these calculations may be done using an overdetermined system of equations.

[0041] The process is repeated at least once starting at **401** for a different field gradient, thus defining a plurality of equations of the form shown in **eqn.(16).** If only one additional field gradient is used, then solution is given by **eqns. (17) – (18).** If additional field gradients are used, then solution is obtained by solving **eqn. (19).**

[0042] Using the computed values of the T_2 distribution and the diffusion distribution, several parameters of interest of earth formations may be determined. These include but not limited to total porosity, clay bound water, bound volume irreducible, gas and oil saturation.

[0043] The method of the present invention is described above with reference to a wireline-conveyed NMR logging tool. The method may also be used on logging tools conveyed on coiled tubing in near horizontal boreholes. The method may also be used on NMR sensors conveyed on a drilling tubular, such as a drillstring or coiled tubing for Measurement-While-Drilling (MWD) applications.

[0044] While the foregoing disclosure is directed to the preferred embodiments of the invention, various modifications will be apparent to those skilled in the art. It is intended that all variations within the scope and spirit of the appended claims be embraced by the foregoing disclosure.